HYBRID POWER – AN ENABLING TECHNOLOGY FOR FUTURE COMBAT SYSTEMS

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Abstract

For nearly two decades futuristic weapon systems, including lasers, high power microwave systems, and electric guns, have been in various stages of research and development. Such weapon systems may have potential to substantially increase our capability to defeat enemy forces with significantly less logistics burden.

Despite dedicated efforts to study and demonstrate the utility of such weapons and despite many significant advances in the state-of-the-art for some critical technologies, a vast majority of the military community does not project that these weapons will be incorporated into the designs of ground combat platforms in the near future.

The major barrier preventing advanced concepts from being weaponized is the lack of compact pulsed power systems required for operating them. In fact the desire for future combat systems to become more mobile, lighter and smaller seems to conflict directly with the desire to utilize advanced weapon systems in new vehicle designs. Pulsed power sources that have been developed for advanced weapons add too much weight and volume to already overstressed mechanical systems if these new systems are incorporated into future combat vehicle concepts.

The DARPA Combat Hybrid Power Systems (CHPS) program was established to investigate hybrid electric power systems that might provide all the energy and power needs of improved future combat vehicles – specifically the transient, continuous and pulsed power necessary to drive advanced weapons systems, mobility systems, communications systems and protective systems. By exploiting the benefits of hybrid power, power management and power sharing, it may become possible to design future combat vehicles with advanced weapons and protection systems, while reducing logistical requirements (by increasing efficiency) and reducing overall weight and volume.

This paper will describe the CHPS program goals and accomplishments as well as provide insight on how the CHPS approach to design of future vehicles is an essential step toward demonstrating lightweight, future ground combat vehicles capable of improved mobility, lethality, survivability and sustainability.

I. INTRODUCTION

Many current U.S. combat vehicles are nearing the end of their useful service lives. At the same time we find that the roles and missions of the U.S. military are being changed or modified in response to the need for flexible, agile, effective military forces in the rapidly changing global social and political environment. Projections of how we will have to fight in the future require us to explore ways to improve combat systems performance in terms of lethality, survivability, transportability, mobility & agility, strategic & tactical deployability, and sustainability.

Improving the effectiveness of combat systems while reducing their footprint is vital – both to enable rapid deployment and to maintain military dominance with a reduced number of personnel and vehicles. In addition, it is essential to improve subsystem and total system efficiency in order to decrease reliance on fossil fuels and to reduce the costs associated with logistical support.

Army Force XXI concepts for the 2010 timeframe and the Army After Next concepts for 2020/2025 have been envisioned to employ a variety of advanced weapons systems and protective systems in combination to achieve their goals. By adding requirements for vehicles to address multiple missions (such as direct fire support, air defense, and scout/RSTA on the same platform), these concepts offer a way to reduce the total number of vehicles on the battlefield (thereby reducing the logistics tail.) However, these concepts present serious problems for the conventional vehicle designer who has limited trade options. The usual practice is to trade off weight and volume of weapon systems or protection to get deployability and mobility that are central to most future concepts of operations.

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14. ABSTRACT
For nearly two decades futuristic weapon systems, including lasers, high power microwave systems, and electric guns, have been in various stages of research and development. Such weapon systems may have potential to substantially increase our capability to defeat enemy forces with significantly less logistics burden. Despite dedicated efforts to study and demonstrate the utility of such weapons and despite many significant advances in the state-of-the-art for some critical technologies, a vast majority of the military community does not project that these weapons will be incorporated into the designs of ground combat platforms in the near future. The major barrier preventing advanced concepts from being weaponized is the lack of compact pulsed power systems required for operating them. In fact the desire for future combat systems to become more mobile, lighter and smaller seems to conflict directly with the desire to utilize advanced weapon systems in new vehicle designs. Pulsed power sources that have been developed for advanced weapons add too much weight and volume to already overstressed mechanical systems if these new systems are incorporated into future combat vehicle concepts.

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The DARPA Combat Hybrid Power Systems (CHPS) program is exploring one avenue that might make it possible to integrate multiple subsytems in an more efficient way so that designers may be able to fit more capability into smaller, lighter vehicles. Clearly, there are technology improvements and breakthroughs in the area of power system components that will be enabling. But the key to open the door will be development of *centralized power control for all systems in the vehicle and power management* through a flexible distribution network.

In the CHPS program we will demonstrate various power system architectures and power management and control strategies to drive multiple electrical loads. Figure 1 shows the CHPS system concept.

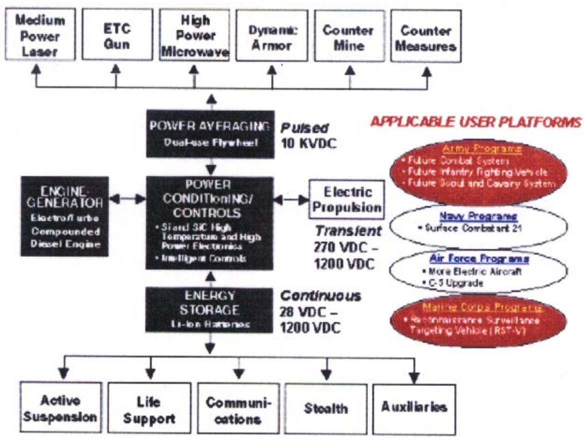

Figure 1. CHPS System Concept

The CHPS concept uses pulsed power sources, such as flywheel systems, combined with continuous power sources, such as engines and batteries, to work together to provide the power and energy needed to drive pulsed loads such as: high power microwaves, lasers, EM/ETC guns or Active protection systems. The result is a flexible hybrid system architecture that can drive a variety of loads in a smaller footprint using fewer components. In addition, new capabilities, such as silent operations for all ground combat vehicles, can be considered.

II. BACKGROUND

The CHPS program was initiated as one of several programs to address commercial and military incentives to move towards the electrification of vehicles. Many of the efforts, although conducted under separate programs, have clear linkages and were constructed to compliment one another with respect to demonstrating critical technologies and investigating issues associated with making hybrid electric combat vehicles of all weight classes a reality. This section outlines the basics of hybrid electric propulsion and identifies some of the programs related to the CHPS program.

A. Hybrid Electric Power for Propulsion

Vehicle propulsion can be accomplished with several different drive train configurations as shown in Figure 2.

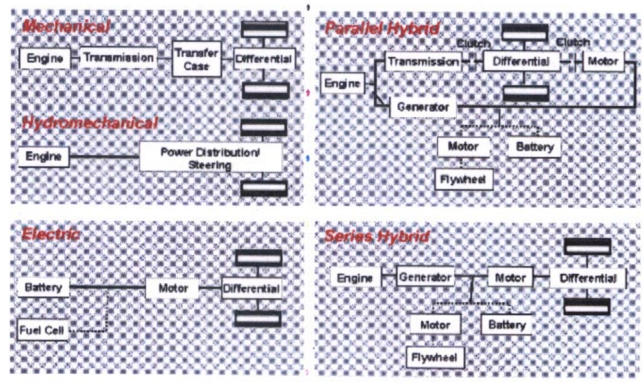

Figure 2. Drive train Configurations

Hybrid power systems provide improved drive train efficiency when compared to mechanical systems mainly because prime movers (traditionally internal combustion engines) can be engineered to operate at their "sweet spot" (the point where fuel consumption is the lowest) 100% of the time to generate electrical power to the distribution network. In hybrid systems batteries or rotating machines store energy that can be used to provide the power needed for acceleration and to recover the energy normally lost in braking. By using intelligent control strategies for the system improved system efficiency can be translated into significant fuel savings and reduced emissions. The amount of fuel savings that can be achieved with a hybrid electric drive system is highly dependent on the vehicle driving profile.

Studies of both commercial and military vehicles have shown that overall thermal efficiencies can approach 40%, versus the typical 15% for pure mechanical systems for many typical driving missions. Overall system efficiency can be improved even more by exploiting component technologies.

DARPA has two programs that specifically relate to hybrid electric vehicles. *The Electric and Hybrid Electric Vehicle Technology Program* is a joint effort with the Department of Transportation in which electric and hybrid electric drive technologies are being fabricated for both commercial and military applications. Under this program commercial busses have been developed and are being tested to benchmark performance in several locations around the country. Hybrid electric military vehicles developed under this program include a M113, a HMMWV and a Bradley Fighting Vehicle. Under the Reconnaissance, Surveillance and Targeting Vehicle (RST-V) Program, DARPA is developing a V-22 transportable vehicle with hybrid electric power/propulsion in conjunction with the U.S. Marine Corps. This vehicle will demonstrate increased mobility, increased fuel economy, silent watch capability, plus the ability to perform RST missions and power management in a compact, lightweight (4 ton) mobile platform. More

information on these programs can be found on the DARPA web site (http://www.darpa.mil.)

III. THE CHPS PROGRAM

The CHPS program transcends all existing electric and hybrid electric vehicle programs in two ways. First, CHPS is focused on designing and demonstrating the hybrid electric concept applied to a ground combat vehicle using a total system approach. For the first time, we will demonstrate the ability to operate integrated prime power, energy storage and pulsed power components through a single DC bus with load management while simultaneously supplying realistic, multiple, continuous and dynamic ground combat vehicle loads. Secondly, we are developing a flexible, modular, end-to-end model for hybrid electric vehicle systems that may serve as the basis for designing and evaluating all weight classes and types of future combat systems. This virtual prototype should significantly reduce the costs associated with having to build multiple prototype vehicles to evaluate the performance of future concepts.

A. CHPS Program Overview

The CHPS program has three major goals:

- Develop and demonstrate hybrid electric power systems for 15-ton class combat vehicles in a Systems Integration Laboratory (SIL). The SIL allows for future scaling up or down for flexible testing of all vehicle classes.
- Use virtual prototype models to validate designs for all Future Combat Vehicles.
- Develop and demonstrate high payoff and enabling power system critical component technologies.

In contrast to earlier electric and hybrid electric vehicle programs, CHPS will use its hybrid configuration to address lethality and survivability in addition to mobility. While earlier vehicles have successfully incorporated continuous energy storage with the vehicle propulsion, none have been configured to address combat vehicle loads that require pulsed power. For the first time, the CHPS program will demonstrate the operation of engine, flywheel, motors, and batteries, for example, in a system that will simultaneously provide pulsed and continuous power to combat level loads.

B. CHPS Architecture

As a series hybrid configuration, the CHPS architecture uses a common DC bus to centrally shuttle power. Key components are:

- Prime power – supplied by an engine-generator
- Pulsed power – supplied by both an electromechanical source and battery bank
- Continuous power – supplied by both the prime mover and battery bank.

The hybrid architecture allows for flexibility in power and energy flow to required vehicle systems depending on prospective missions or driving scenarios. Power and energy is available to drive weaponry, mobility or protective loads individually or concurrently.

C. CHPS VIPER-DT

The CHPS Vehicle Integration Performance and Design Tool (VIPER-DT) is being developed to create and analyze vehicle architectures in a virtual environment. Using a series of models and simulations, system and subsystem components are built, integrated and tested, giving insight to design criteria. A continual evaluation of new technologies and configurations allows for focused decisions as to which hardware efforts are practical. A wide variety of vehicle configurations operating under diverse conditions can be simulated without costly developments and testing. The CHPS VIPER-DT is shown in Figure 3.

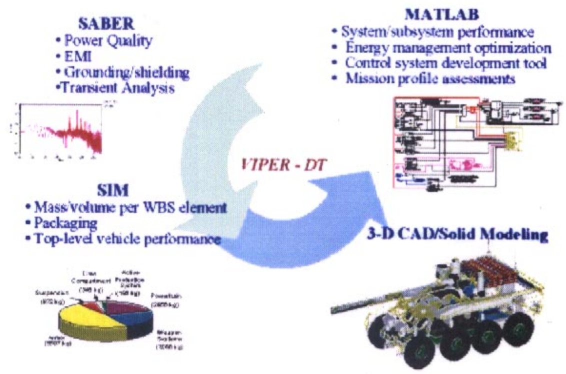

Figure 3. CHPS VIPER-DT Design Tools

This tool set consists of:

- System Integration Methodology (SIM) Tool - a high level evaluation spreadsheet matrix that allows for quick assessments of component capabilities. The SIM tool also tracks initial weight and volume for a first-order understanding of trade-offs.
- MATLAB/Simulink Tools – detailed mathematical and physical models of individual components are constructed, integrated, and analyzed in this tool. A high level of fidelity allows these powerful models to accurately reflect real-world conditions. Subsystem and system wide analyses can be performed.
- SABER – used for electrical analysis of specific CHPS parameters, such as grounding and EMI.

- 3-D CAD & Solid Modeling – weight and volumetric attributes are tracked to maintain a small envelope. Without proper consideration for weight and spacing, systems and subsystems could move beyond practicality for use in a combat vehicle.

VIPER-DT efforts are closely tied to the SIL – as dynamic testing is performed in a real-world environment, simulation validation is available to refine the VIPER-DT models. Exercising VIPER-DT highlights what testing is important and can provide input control conditions to the SIL. The tool set as a whole offers strong simulation capability and will allow for the continual addition of new technologies as they are realistically modeled.

D. CHPS Critical Technologies

The CHPS program is developing key technologies critical to hybrid military vehicles. These technologies, while of interest to the electric vehicle industry in general, must meet more demanding requirements in military vehicles. Components capable of meeting high voltage, high current and high temperature demands found in combat platforms are not commercially available and are not being developed commercially. Robust components are crucial to demonstrating hybrid configuration feasibility as well as for reducing the weight and volume of combat vehicles. The technologies identified by CHPS as requiring specific investigation include advanced batteries, electromechanical pulsed power sources (such as flywheels), advanced prime power units, and high density power electronics (incorporating advanced materials such as silicon carbide and high temperature silicon).

D.1. Lithium Ion Batteries

Lithium Ion (Li Ion) battery technology appears to offer leap-ahead opportunities in the area of energy storage for hybrid electric vehicles. The CHPS program is pushing the state-of-the-art, developing new packaging and models and exploring the performance characteristics of all the Li Ion battery types.

Packaging concepts that result in high density for the CHPS Li Ion battery are shown in Figure 4.

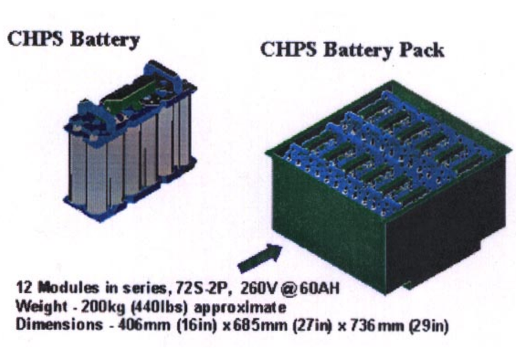

Figure 4. Conceptual CHPS Battery Pack

Figure 5 shows comparisons of various standard battery types (lead acid, NiCd and NiMH) and the Li Ion battery types.

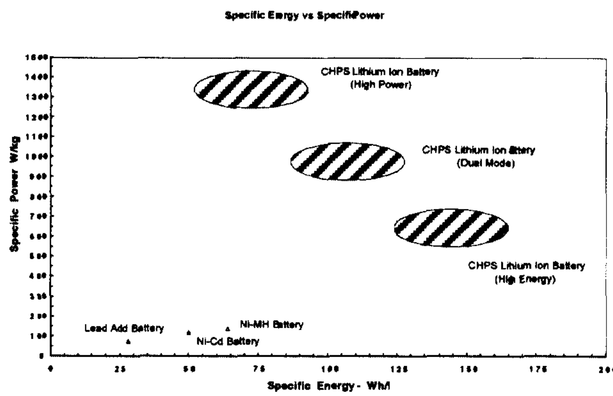

Figure 5. Battery Comparison

As part of the characterization effort, testing is currently underway at the Army Research Laboratory to determine Li Ion battery high-current thresholds.

D.2. Electromechanical Power Sources

Flywheel systems have been demonstrated as practical in commercial use overseas, providing energy recovery from braking, energy storage and pulse power for acceleration in hybrid electric buses. CHPS flywheel investigations have included the design of a 25 MJ composite machine and fabrication of critical flywheel components required for multi-megawatt, multi-megajoule vehicle functions and to power potential weapon systems. Efforts to date include fabrication of the composite rotor, permanent magnet assembly spin testing, fabrication and testing of magnetic and back-up bearing systems, and safety studies. Examples of complete flywheel system designs are shown in Figure 6.

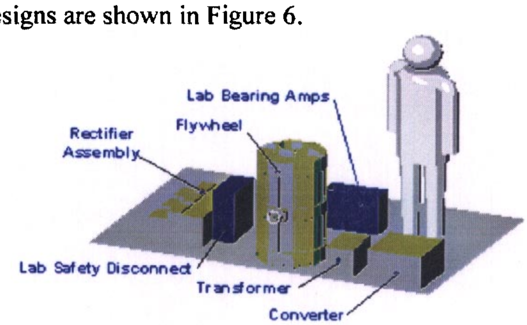

Figure 6. CHPS Initial Flywheel System

D.3. Silicon Carbide Power Electronics

The CHPS program is developing SiC power electronics components to exploit the characteristics of silicon carbide, namely ability to operate at high temperature, high frequency and high current density. SiC power electronics promise to reduce space and weight required for essential conversion, control and switching elements in the hybrid electric power system. A variety of applications have been investigated, including high power inverters (300 kW

continuous / 1 MW pulsed) and high power DC/DC converters (250 kW). Compared with traditional silicon versions of these components, carbide versions offer significantly improved densities (on the order of 50 times) at higher power levels (1.6 times).

E. CHPS SIL – Systems Integration Laboratory

The CHPS System Integration Laboratory (SIL) is a 100% hardware in the loop tool to test hybrid system components and understand all integration and interoperability issues associated with their combined operation. The SIL provides a cost effective, flexible method to bring all the pieces together for testing and evaluation of system performance.

The SIL includes all major components and loads (either real or simulated) in a testing environment that allows real-world scenarios and dynamic conditions to be applied. The SIL replicates the hardware interactions of a true combat vehicle and can physically test the CHPS configuration without the full development of a vehicle. Everything from demanding sequential operation of components to temperature effects can be simulated. The SIL layout and major components, located in San Jose, CA, is shown in Figure 7.

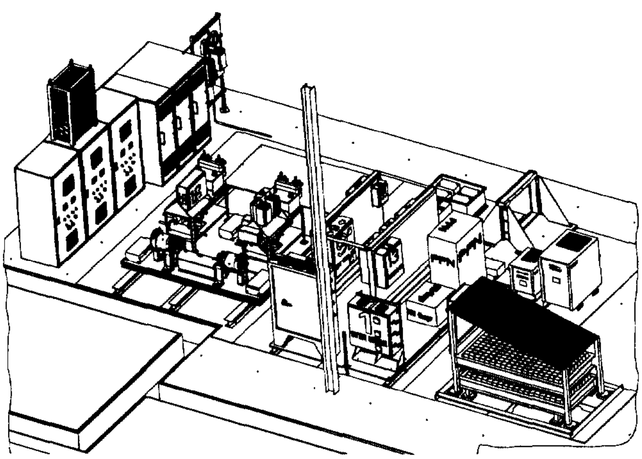

Figure 7. CHPS SIL Layout

In developing the SIL, the CHPS team members have methodically addressed all issues associated with an integrated high power, high energy electrical system. Factors that have required significant effort are:

- Integrated controls development
- Electromagnetic interference (EMI)
- Grounding and shielding
- Air and fluid cooling requirements
- Safety
- High and low speed data acquisition
- Electrical noise (integration of AC and DC components at different voltage levels and frequency)
- Physical configuration and placement
- Interconnects and wiring runs

Currently, the SIL is at the mid-point of its milestone development schedule and will be fully operational in the year 2000.

IV. HYBRID SYSTEMS FOR PULSED POWER

Vehicle hybrid power systems allow for unique configurations that address their power and energy requirements. For example a hybrid automobile uses a combination of prime power, typically supplied by an internal combustion engine, and energy storage, typically supplied by a battery bank. The prime power and energy storage elements can be used individually to meet the continuous energy requirements of the vehicle, with both being used together to meet the infrequent periods when high power is needed (i.e. acceleration, hill climbing). As hybrid power systems were applied to larger vehicles, such as passenger buses, the high power periods become more frequent and higher in magnitude. Additional high power capability was needed and resulted in pulsed power sources, such as flywheels, for load leveling.

When hybrid power systems are considered for application in combat vehicles, we begin to see energy and power requirements that greatly exceed those of commercial vehicles in magnitude and frequency. Hence, well-engineered combinations of energy and power availability and delivery are crucial. The DARPA CHPS program has made progress in understanding intelligent and efficient mixes of continuous and pulsed power.

A. Pulsed Power for Mobility

Hybrid power is often desired to reduce vehicle fuel consumption without sacrificing performance. To reduce consumption, smaller prime power units are utilized that operate at a single, highly efficient, operating speed. However, it is well understood that vehicles (especially very heavy, high performance military vehicles) require high amounts of torque under certain conditions. Examples include rapid acceleration, hill/grade climbing, and off-road maneuvering. Typically, mechanical transmissions combined with higher RPM (and hence higher torque) engine operations are used for these conditions.

Since engines on hybrids are now used for single speed operation in a power generation role, pulsed power sources that provide load leveling (the additional provided over and above the baseline power) are required to augment the engine. A properly engineered hybrid system will keep the prime power engine small – sized for typical continuous operation. The pulsed power augmentation will also be small and only sized for those high power conditions. Stand-by efficiency of the pulsed power source is crucial to limit parasitic losses when pulsed power is not needed.

The mechanical advantages gained by a hybrid system are impressive. When continuous and pulsed power for mobility is properly combined, the electric drive will produce much improved acceleration due to the instantaneous response of the electric wheel drive motors.

Torque availability is also greatly improved. For example, the CHPS NCV contains a 280 hp prime power unit. When combined with the pulsed power sources, 0-60 mile-per-hour acceleration can be achieved in 15 seconds. If the 15-ton vehicle used the traditional mechanical engine/transmission configuration, a prime power unit in excess of 1000 hp would be required as shown in Figure 8.

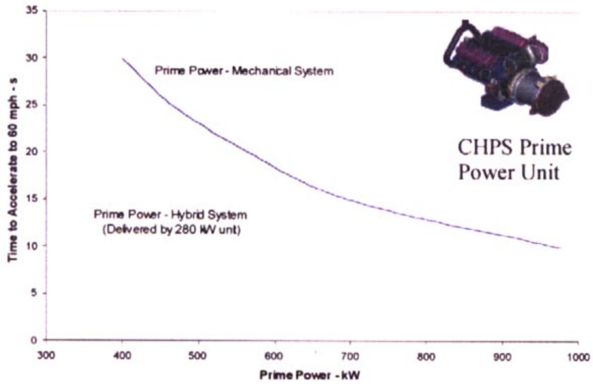

Figure 8. Hybrid vs. Non-Hybrid Prime Power Comparison

B. Pulsed Power for Weapons/Defensive Systems

Hybrid power systems offer pulsed power capabilities never before available on combat vehicles. A fully integrated electrical system allows for the bundling of system capabilities that in conventional combat vehicles must be supplied by individual and non-synergistic subsystems. The benefits are reduced size and weight with added capability.

New weapons and protective systems concepts exist that require pure electric energy (as opposed to mechanical or chemical). Pulsed power requirements are in the MW to GW range on the high end, and typically require MJ energy levels. For CHPS, the critical technology development efforts have aimed for the following goals:

- Rotating machines capable of delivering:
  25 MJ @ 20,000 RPM
  ~ 1000 kg system weight
  ~ 674 liters system volume
- Batteries capable of delivering:
  1. 50 kWh of energy
     < 850 kg, < 350 liters
     1000's of A for 100's of ms
  2. 50 kWh of energy
     < 400 kg, < 200 liters
     100's of A for 10's of s
- Prime power diesel unit capable of 280W continuous power

All components are tied into a central 525 VDC bus. Pulsed loads will be driven by a 200 kJ, 10 kV Pulse Forming Network (PFN) capable of being recharged 0.2s by a 250 kW SiC DC/DC converter (525V to 10 kV).

With such component capabilities, flexibility is available between the different power and energy sources. Trade studies are underway using the VIPER-DT tools to estimate, for example, battery pack and flywheel sizes based on battery test data. One set of results is shown in Figure 9.

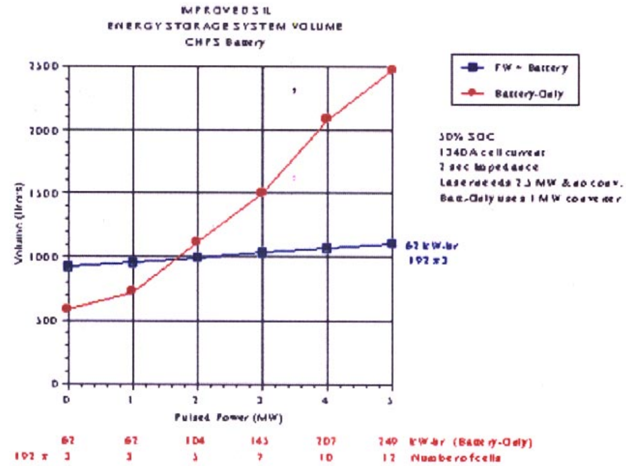

Figure 9. Trade-off Studies - Pulsed Power Components

VI. CONCLUSIONS

The DARPA CHPS program is providing a series of tools that quantify and test integration and interoperability issues associated with hybrid power systems for combat vehicles. Included with the improved performance of hybrid systems over conventional mechanical systems is the ability to drive high power and high energy pulsed loads, such as emerging weapons and protective systems. The total hybrid architecture offers improved performance and capability with increased efficiency. The CHPS tools will continue to offer a platform where exploration of pulsed loads (in the multi-MW, multi-MJ ranges) integrated with continuous loads can be performed using low-cost virtual and hardware resources.

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